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Management-induced greenhouse gases emission mitigation in global rice production

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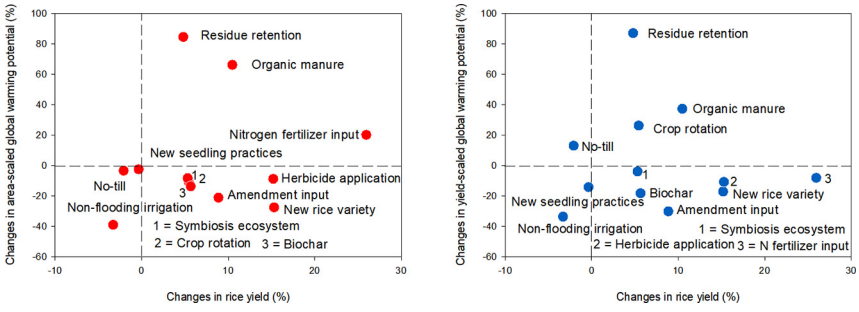
HIGHLIGHTS

- 12 paired field management practices were assessed using a global meta-analysis.
- Adjusted practices could reduce GWP highly by 39.1% mainly due to CH_4 mitigation.
- The increased yield under adjusted practices can offset the yield-scaled GWP.
- High yield and low emission strategy needs to consider interactions with soil/climate.

GRAPHICAL ABSTRACT



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ABSTRACT

Mitigating greenhouse gases (GHGs) emissions from rice paddy (*Oryza sativa* L.) and balancing the trade-offs between reducing emission and sustaining food security have raised global concerns. A global meta-analysis of rice experimental data was conducted to assess changes in emissions of GHGs (CH_4 and N_2O) and global warming potential (GWP) in response to improvements through 12 field management practices. The results indicated that changes in GWP were mainly attributed to CH_4 emission even though N_2O emission was significantly affected by conversion of field management practices. Specifically, GWP per unit rice plant area (area-scaled) was significantly increased by 20.1%, 66.2%, and 84.5% with nitrogen (N) fertilizer input, manuring, and residue retention ($P < 0.05$), along with significant increments in area-scaled CH_4 emission under the above management practices by 8.9%, 60.4%, and 91.8%, respectively ($P < 0.05$). Due to the significant increase in rice yield, a decreasing trend for GWP per unit rice yield (yield-scaled) was observed with N fertilizer input. In addition, CH_4 and GWP decreased significantly at both area- and yield-scale under non-flooding irrigation but with a reduction in rice yield by 3.3% ($P < 0.05$). Improvement in rice variety significantly enhanced crop yield by 15.3% while reducing area-scaled GWP by 27.7% ($P < 0.05$). Furthermore, other management practices, such as application of herbicides, biochar, and amendments (non-fertilizer materials) reduced yield-scaled GWP while increasing rice yield. Thus, changes in field management practices have the potential to balance the trade-offs between high yield and low emission of GHGs. However, in-depth studies are needed to determine the interactions between field management practices and site-specific soil/climate conditions.

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1. Introduction

Feeding the world's growing population under the changing climate is a serious global concern. Concerted efforts have been made to both enhance crop production and mitigate climate change (Foley et al., 2011; IPCC, 2014; Kahiluoto et al., 2014; Lal, 2004). Despite of a strong capacity to store carbon (C) (Batjes, 1996; Lal, 2004), agriculture soil is also a major anthropogenic source of greenhouse gases (GHGs, e.g. CO_2, CH_4, and N_2O), which occupies over 13% of the total GHGs emissions, especially 60% of CH_4 and 61% of N_2O emission (IPCC, 2013). Thus, reduction in emissions of agricultural CH_4 and N_2O may be pertinent to mitigate global changing climate (Tian et al., 2016). Rice is an important food crop and is essential to global food and nutrition security (Seck et al., 2012). However, CH_4 emission from rice paddy was estimated to occupy 48% of total GHGs emissions in global croplands (Carlson et al., 2017). While reducing CH_4 emission from rice paddies is an effective strategy to mitigate global climate change, it must be considered along with sustaining rice production and increasing the agronomic yield because of the ever-increasing demand for food (Foley et al., 2011; Ray et al., 2012). Therefore, there are needs for identifying the effects of CH_4 mitigation strategies on rice yield, analyzing the relationships between cutting CH_4 emission and enhancing rice yield under those mitigation adoptions.

Effects of different management techniques on rice yield and GHGs emissions have been widely documented on local, regional, national and global scales. Increases in rice yield have been achieved with positive or negative effects on CH_4 and/or N_2O emissions (Fagodiya et al., 2017; Liu et al., 2014; Weller et al., 2016; Zhang et al., 2013). A thorough understanding of the nexus of crop yield - GHGs emissions - field management practices is needed. The GHGs emissions per unit of rice yield (such as yield-scaled CH_4) may be a more effective indicator of the potential trade-offs between mitigating GHGs and enhancing crop production than emissions per unit area (Carlson et al., 2017; Feng et al., 2013; van Groenigen et al., 2013; van Kessel et al., 2013). Thus, worldwide efforts have been made to reconcile the goal of reducing CH_4 emission with increasing rice yield, including changes in irrigation methods, tillage practices, fertilization, etc. (Ali et al., 2013; Bayer et al., 2014; Li et al., 2013; Linquist et al., 2012). However, benefits of reduction in CH_4 emission to climate change are offset if the practices significantly increase the emission of N_2O because it has a higher global warming potential (GWP) than CH_4 (IPCC, 2013). Furthermore, some management practices have opposite effects on CH_4 and N_2O emissions. Results of regional and global meta-analysis showed that no-till (NT) (Zhao et al., 2016) and intermittent irrigation (Feng et al., 2013) could reduce CH_4 emission and increase N_2O emission. Residue retention tended to increase CH_4 emission and decrease N_2O emission in paddy soil (Liu et al., 2014). However, it is still unclear to what extent changes in N_2O could offset the benefits of CH_4 mitigation for many field management practices on a global scale. Thus, integrating emissions of CH_4 and N_2O by their GWPs is a useful approach to comprehensively and accurately evaluate the management-induced responses to climate change mitigation.

The trade-offs between mitigating climate change and enhancing rice production by management options have been widely reported especially at the yield-scaled scenario (Ali et al., 2013; Feng et al., 2013; Pittelkow et al., 2013; Tao et al., 2016; Xiong et al., 2015). However, there is lack of global comprehensive assessment on balancing the trade-offs between climate change mitigation and food supply for a range of management practices in rice production. In this study, we tried to verify the hypothesis that adjusted management practices could reduce the GHGs emissions but increase rice yield substantially. Therefore, the objectives of this study were to generate a global dataset on CH_4 emission under climate-smart field practices in rice production, determine the mitigation effects on GWP with consideration of attendant effects on N_2O emission, analyze the relationships between CH_4 and N_2O emission, evaluate the balancing of trade-offs between mitigating GHGs and sustaining rice yield especially in the term of yield-scaled, and advance the understandings of the potential of adjusting field management practices for reducing GHGs emissions while also enhancing rice production.

2. Materials and methods

2.1. Data collection

The data were collected from research articles from Web of Science (WOS, http://apps.webofknowledge.com/) and the China Knowledge Resource Integrated Database (CNKI, http://www.cnki.net/) published before 2017 with key words of "rice or padd*" and "methane or CH_4 emission". The selected articles were those with the theme of CH_4 emission affected by field management practices conducted at the site-specific rice fields. The following criteria were used to filter the paired experiments: (1) studies should be designed as side-by-side paired-plot field experiments in rice field; (2) absolute emission of CH_4 was provided or could be calculated and conducted with closed chamber method for the entire rice growing season; (3) field management practices, treatments, and controls were described in detail in each study; and (4) the location of the experiment was provided. The data for the N_2O emission and rice yield were also extracted from filtered articles. Finally, 2616 comparisons (1155 for CH_4 emission, 741 for N_2O emission, and 720 for rice yield) from 230 publications (159 from WOS and 71 from CNKI) were selected to compile the meta-analysis dataset. Fourteen countries (Supplemental Fig. 1) involved in the dataset included the most important rice growing areas and the top producers.

Twelve types of field management practices were assessed for the effects on GHGs emissions and rice yields. Treatments and controls were included in the comparison according to the detailed description of the practices in all the eligible studies (Table 1). The 12 comparisons of management practices were as following: new seedling practices compared with conventional seedling practice, herbicide application compared with no herbicide application, crop rotation compared with continuous rice, symbiosis ecosystem (rice-duck, rice-fish, rice-floating vegetation systems) compared with paddy-rice system, residue retention compared with residue removed, no-till (NT) compared with conventional tillage, new rice variety compared with traditional rice variety, biochar application compared with no biochar adoption, non-flooding irrigation (reducing irrigation amount or time, enhancing middle season drainage) compared with flooding irrigation, organic manure application compared with no manure, amendment input (non-fertilizer materials,

Table 1
Overview of field management comparisons and matching number of publications in the meta-analysis.

Field managements	Number of publication			Numbers of country
	CH_4	CH_4 and yield	CH_4 and N_2O	
New seedling practices[a]	19	16	14	5
Herbicide application	5	4	4	2
Crop rotation[b]	11	5	10	3
Symbiosis ecosystem[c]	13	4	6	2
Residue retention	65	37	43	9
No-till	17	7	10	2
New rice variety	24	13	9	4
Biochar	13	13	13	4
Non-flooding irrigation[d]	55	40	32	12
Organic manure	52	29	28	7
Amendment input[e]	14	10	9	5
Nitrogen fertilizer input	80	44	53	9

[a] Increase in plant density, postponed seeding date, labor saving seeding methods (by machine and etc.).
[b] Cover crop in fallow season, rotation with upland crops (rice-wheat, rice-maize, rice-rape rotation, and etc.).
[c] Rice-duck, -fish, -floating vegetation system.
[d] Reduced irrigation amount or time, enhanced mid-season drainage.
[e] Nitrification and urease inhibitors, phosphogypsum, methane inhibitor, steel slag etc.

such as nitrification and urease inhibitors, phosphogypsum, methane inhibitor, steel slag etc.) compared with no amendment adoption, and N fertilizer input compared with no N fertilizer. Among the 12 paired management practices, subgroups of new seedling practices (increase in plant density, postponed seeding date, or labor saving seeding methods), crop rotation (cover crop in the fallow season, or rotation with upland crops), residue retention (incorporation into soil, mulching on surface, or ditch buried into soil), and N fertilizer input (increasing in nitrogen amount, or controlled releasing fertilizer or fertilizing at growth stage) were divided to assessed the detail changes of GHGs emissions and rice yield under specific paired practices, the related information is shown in Supplementary Tables 1–4. The selected articles were listed in Supplementary Note and the related information was listed in Supplementary Dataset.

2.2. Data preparation

The values of cumulative seasonal emissions of CH_4 and N_2O were included directly in the dataset for the articles that provided this information. For studies which reported the emission flux data (e.g. mg m^{-2} h^{-1}), the cumulative seasonal emissions were computed by multiplying the flux data by the corresponding growth period. For those which presented the emissions in the form of CO_2 equivalents (CO_2-eq ha^{-1}), the values were divided by 298 for N_2O and by 25 for CH_4, respectively (IPCC, 2007). For studies that reported the emissions as CH_4-C and N_2O-N, the data were transformed using the molecular mass as a conversion factor (16/12 for CH_4 and 44/28 for N_2O). For those which reported both the GHGs (CH_4 and N_2O) emissions and rice yield, the area-scaled GWP was computed by using the Eq. (1) (IPCC, 2013):

$$\text{Area-scaled GWP} = CH_4 \times 25 + N_2O \times 298 \quad (1)$$

where, CH_4 and N_2O are the mean area-scaled CH_4 and N_2O emission (kg ha^{-1}), respectively. The yield-scaled emission was computed from the area-scaled emissions divided by rice yield.

2.3. Meta-analysis

A meta-analysis was conducted to assess management-induced changes in emissions of CH_4 and N_2O, and GWP at both area-scaled and yield-scaled scenarios, as well as the changes in rice yield. The natural log (ln$R$) of the response ratio was calculated as the effect size of this meta-analysis by using Eq. (2) (Hedges et al., 1999):

$$\ln R = \ln\left(\overline{\chi_t} \Big/ \overline{\chi_c}\right) = \ln\overline{\chi_t} - \ln\overline{\chi_c} \quad (2)$$

where, $\overline{\chi}$ is the mean value of area-scaled emission of CH_4, N_2O, and GWP, rice yield, and yield-scaled emission of CH_4, N_2O, and GWP under treatment (t) and control (c) of each observation, respectively. For some of the observations in the dataset presented herein, the standard deviation values were not available in the compiled studies. Thus, replication was used to calculate the weight of the individual observations by using Eq. (3) (Adams et al., 1997; Pittelkow et al., 2015):

$$w = (n_t \times n_c)/(n_t + n_c) \quad (3)$$

where, w is the weight of each ln$R$ of observations, n is the corresponding replication for treatment (t) and control (c). For scenarios where more than one observation from a study was included in the same category, weights were divided by the total number of observations from that study. The meta-analysis was conducted with Metawin 2.1 (Rosenberg et al., 2000). The weighted mean effect size and 95% confidence interval (*CI*) were generated by bootstrapping (4999 iterations), and the between-group heterogeneity was assessed by using randomization procedures with 4999 replications (Adams et al., 1997; Pittelkow et al., 2015). If the 95% *CI* did not overlap with zero, the treatments were reasoned to represent a significant increase (>0) or decrease (<0) compared to the controls ($P < 0.05$). For ease of interpretation, results were back-transformed and reported as percentage change (E) by using Eq. (4):

$$E = \left(e^{\ln R} - 1\right) \times 100 \quad (4)$$

As pointed out by Philibert et al. (2012), publication bias and sensitivity analysis are necessary in meta-analysis. Normal Quantile plot (Rosenberg et al., 2000) and Jackknife technique (Philibert et al., 2012) were used to assess the publication bias and sensitivity of weighted mean effect sizes of CH_4 emission to each observation of the dataset for the 12 field management practices, respectively. As for few management practices, the standardized effect sizes did not distribute evenly with the y = x line (Supplemental Fig. 2), and 95% *CI*s (Supplemental Fig. 3) were shifted when remove individual observations. However, this did not significantly affect the conclusions of this meta-analysis.

3. Results

Overall, among the 12 paired field management practices, non-flooding irrigation was the most efficient practice in reducing CH_4 emission (area-scaled, Fig. 1a). Significant decreases by 51.5% in CH_4 emission were observed under non-flooding irrigation practices when compared to those under continuous flooding irrigation ($P < 0.05$). Adoption of new rice varieties was also an important alternative to reducing CH_4 emission. An overall decrease of 23.7% in area-scaled CH_4 emission was observed in the present global meta-analysis with the adoption of new rice varieties ($P < 0.05$). The amendments (non-fertilizer materials such as nitrification, urease inhibitors and etc.) included in the analysis significantly reduced the area-scaled CH_4 emission by 16.6% ($P < 0.05$). However, no significant changes in area-scaled CH_4 emission were observed with the adoption of new seedling practices, herbicide application, crop rotation, symbiosis ecosystem, NT, and biochar application. Within these practices, significant heterogeneity was observed among specific management practices of new seedling practices and crop rotation ($P < 0.05$, Supplemental Tables 1 and 2). However, residue retention, organic manure application, and nitrogen (N) fertilizer input significantly increased the area-scaled CH_4 emission by 91.8%, 60.4%, and 8.9%, respectively ($P < 0.05$).

The meta-analysis showed that majority of the treatments could significantly increase rice yield (Fig. 1b). Compared to no N fertilizer application, rice yield was increased by 26.0% with the N fertilizer application ($P < 0.05$). Because of the increase in rice yield, N fertilizer application showed a trend of reducing CH_4 emission on the basis of unit yield. The result presented herein showed a significant decrease in yield-scaled CH_4 emission by 13.1% (Fig. 1c) with the N fertilizer application. Similarly, application of herbicides significantly increased rice yield by 15.2%, which led to a significant decrease in the yield-scaled CH_4 emission by 19.6% ($P < 0.05$). Biochar tended to decrease yield-scaled CH_4 emission (11.9%) more strongly than area-scaled CH_4 emission (6.9%), due to a significant increase by 5.7% ($P < 0.05$) in rice yield. New seedling practices decreased yield-scaled CH_4 emissions by 25.1% (Fig. 1c) and the largest decreases of 35.9% was observed with postponing the seeding date (Supplemental Table 1). Furthermore, the increased rice yield (8.9%) with the amendment input significantly reduced yield-scaled CH_4 emission by 25.0%, which is more than the decrease of area-scaled emission ($P < 0.05$).

Although rice yield was significantly increased by 4.8% with the residue retention (Fig. 1b), CH_4 emission was increased faster than the yield. Thus, there was a higher percentage of increment in yield-scaled emission than that in area-scaled emission (107.0% vs 91.8%, Fig. 1a and c) with residue retention. However, the decrease in yield-scaled

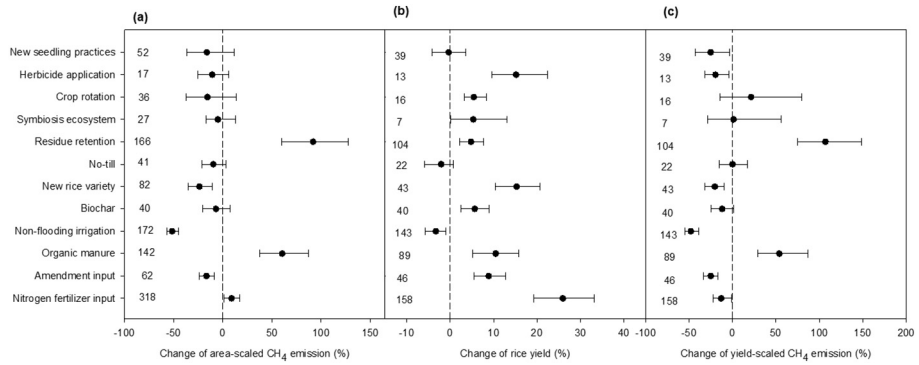
(a)
(b)
(c)
New seedling practices
Herbicide application
Crop rotation
Symbiosis ecosystem
Residue retention
No-till
New rice variety
Biochar
Non-flooding irrigation
Organic manure
Amendment input
Nitrogen fertilizer input
52 17 36 27 166 41 82 40 172 142 62 318
39 13 16 7 104 22 43 40 143 89 46 158
39 13 16 7 104 22 43 40 143 89 46 158
-100 -50 0 50 100 150
-10 0 10 20 30 40
-100 -50 0 50 100 150 200
Change of area-scaled CH4 emission (%)
Change of rice yield (%)
Change of yield-scaled CH4 emission (%)

Fig. 1. Results of meta-analysis on the responses of CH_4 emission and yield of rice to changes in field management practices. (a) change in area-scaled CH_4 emission. (b) change in rice yield. (c) change in yield-scaled CH_4 emission. Numbers near the axis are comparisons in meta-analysis, error bar means 95% confident interval.

CH_4 emission with the adoption of new rice varieties was smaller than that in area-scaled emission (20.3% vs 23.7%), yet the yield can be significantly increased by 15.3% ($P < 0.05$). Additionally, yield-scaled CH_4 emission was significantly reduced by 47.9% under non-flooding irrigation, but with a significant decrease in crop yield by 3.3%. Yield-scaled CH_4 emission was significantly increased by 53.9% with the application of organic manure, which was smaller than that for the area-scaled, mainly due to a significant increase in rice yield by 10.5% ($P < 0.05$). In addition, no significant changes were observed in yield-scaled CH_4 emission despite the significant increases in rice yield by 5.4% and 5.3% under crop rotation and symbiosis ecosystem, respectively.

N_2O emission from paddy rice was substantially smaller than the amount of CH_4 emission. Meta-analysis indicated significant decreases in area-scaled N_2O emission under field management practices of herbicide application and amendment input by 31.3% and 34.3%, respectively ($P < 0.05$, Fig. 2a). However, rice managed with new seedling practices, crop rotation, symbiosis ecosystem, NT, non-flooding irrigation, organic manure application, and N fertilizer input significantly increased the area-scaled N_2O emission by 28.3%, 71.0%, 24.7%, 58.1%, 84.4%, 35.7%,

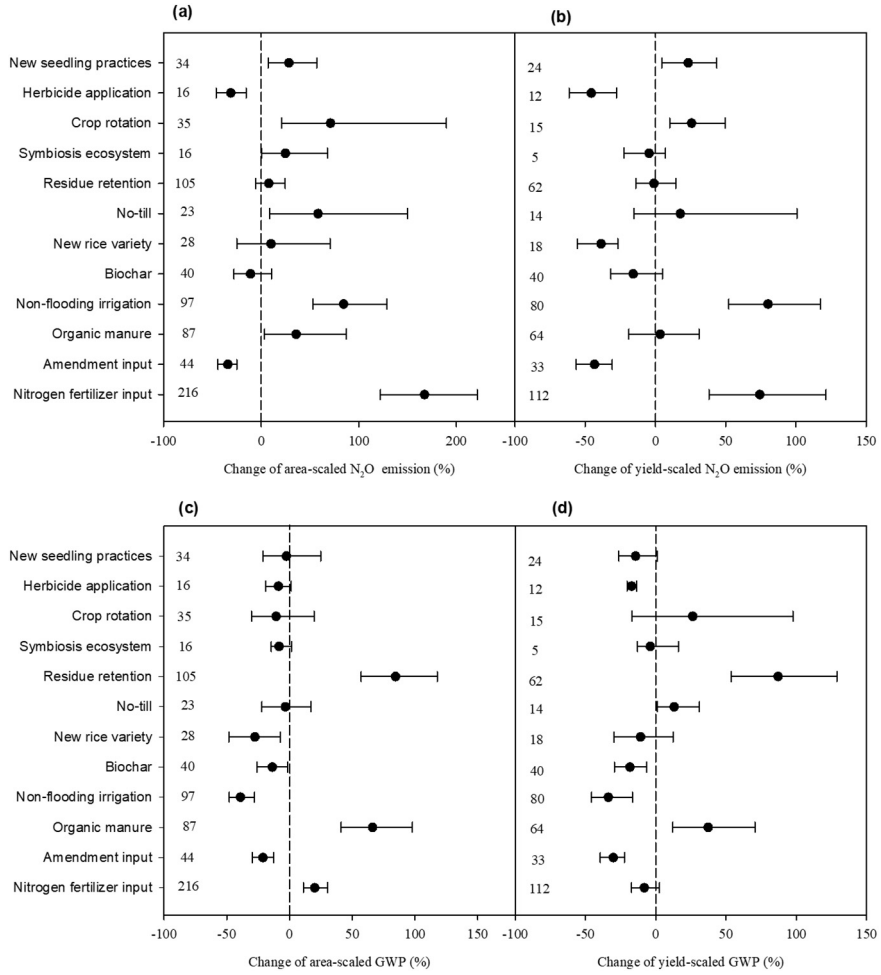

Fig. 2. Results of meta-analysis on the responses of N_2O emission and global warming potential (GWP) of rice to changes in field management practices. (a) change in area-scaled N_2O emission. (b) change in yield-scaled N_2O emission. (c) change in area-scaled GWP. (d) change in yield-scaled GWP. Numbers near the axis are comparisons in meta-analysis, error bar means 95% confident interval.

and 167.3%, respectively ($P < 0.05$). The changes in area-scaled N_2O emission after adding organic materials such as residue retention and organic manure application differed.

The results showed that the increases in rice yield significantly decreased yield-scaled N_2O emission by 45.6%, 38.7%, and 43.3% under herbicides application, new rice variety adoption, and amendment input, respectively ($P < 0.05$, Fig. 2b). However, improved seedling practices, crop rotation, non-flooding irrigation, and N fertilizer input significantly increased yield-scaled N_2O emission by 23.4%, 25.8%, 80.2%, and 74.3%, respectively ($P < 0.05$). In addition, non-significant change in yield-scaled N_2O emission was observed for the rice managed with symbiosis ecosystem, NT, and organic manure application on the basis of per unit yield.

Upon integrating both the changes in CH_4 and N_2O emissions to indicate the comprehensive effects on climate change mitigation, the area-scaled GWP was observed to be significantly increased by 84.5%, 66.2%, and 20.1% with residue retention, organic manure application, and N fertilizer input, respectively ($P < 0.05$, Fig. 2c). However, adoption of new rice variety, biochar, non-flooding irrigation, and amendment input significantly reduced the area-scaled GWP by 27.7%, 13.8%, 39.1%, and 21.3%, respectively ($P < 0.05$). The changes of yield-scaled GWP indicated the efficiency of field management practices to mitigate GHGs emissions and enhance crop production. As an average, yield-scaled GWP could be significantly reduced by 17.2%, 18.4%, 33.8%, and 30.2% by rice production with herbicide application, biochar, non-flooding irrigation, and amendment input, respectively ($P < 0.05$, Fig. 2d). However, significant increases in yield-scaled GWP were also observed with residue retention, NT, and organic manure application by 87.0%, 13.1%, and 37.3%, respectively ($P < 0.05$). Furthermore, no significant changes in GWP at yield-scaled were found for the rice managed with new rice variety and N fertilizer input.

This dataset indicated several instances of opposing treatment effects of management practices on CH_4 emission and rice yield, along with on emission of CH_4 and N_2O. We found a significant positive relationship between effect sizes ($\ln Rs$) of CH_4 emission and of rice yield for the overall 720 observations ($R^2 = 0.05$, $P < 0.0001$, Table 2), especially for new seedling practices ($R^2 = 0.27$, $P = 0.0008$), crop rotation ($R^2 = 0.49$, $P = 0.0024$), biochar application ($R^2 = 0.18$, $P = 0.0057$), and N fertilizer input ($R^2 = 0.05$, $P = 0.0037$). In addition, changes in CH_4 emission was observed negatively related to N_2O emission at both area- and yield-scaled for the overall dataset (Table 2). That indicated the decreases in CH_4 emission may be observed with increases in N_2O emission at area- or yield-scaled. However, changing the N fertilizer input could result in positive related changes in CH_4 and N_2O emission at both area- ($R^2 = 0.03$, $P = 0.0159$) and yield-scales ($R^2 = 0.10$, $P = 0.0005$).

In addition, the responses of CH_4 emission to management practices were observed to be affected by site-specific soil/climate conditions such as mean annual temperature (MAT), mean annual precipitation (MAP), soil pH, BD, and SOC (Supplementary Table 5). The effects of N fertilizer on CH_4 emission were significantly related to soil pH ($r = -0.25$, $P < 0.001$), BD ($r = 0.19$, $P < 0.05$), and soil organic carbon (SOC) ($r = -0.17$, $P < 0.01$). These results suggested that increased CH_4 emission under N fertilizer input could be partly mitigated when increasing soil pH and SOC or decreasing BD. Similarly, management effects of organic manure application were negatively related to soil pH ($r = -0.26$, $P < 0.01$), management effects of residue retention were negatively related to MAT ($r = -0.48$, $P < 0.001$), management effects of no-till were negatively related to MAT ($r = -0.39$, $P < 0.05$) and positively to SOC ($r = 0.36$, $P < 0.05$).

4. Discussion

The quality of the dataset used for this meta-analysis is essential to address the management-induced changes in GHGs emissions and rice yield. Our analysis compared twelve paired field management practices to test the hypothesis that adjusting field management practices could mitigate climate change and maintain crop production. Previous meta-analysis on effects of some specific practices (Jiang et al., 2017; Liu et al., 2014; van Kessel et al., 2013; Zhao et al., 2016) or a package of practices (Feng et al., 2013) have been reported at both regional and global scale. To conduct a comprehensive and effective meta-analysis, our dataset partly draws from previous datasets published by Feng et al. (2013), Liu et al. (2014), and Zhao et al. (2016), along with including additional observations of treatment effects from new publications and different management practices. As a result, the current meta-analysis collected 2616 comparisons from 230 publications can provide an assessment with large representativeness and effectiveness on changes in GHGs emissions and yield of rice production.

Both negative and positive responses were observed in changes of rice yield with changes in field management practices in the present meta-analysis. Substantial decreases in rice yield with adoption of some management practices (e.g., non-flooding irrigation in this meta-analysis) may jeopardize global food security no matter how large the effects on climate change mitigation (Foley et al., 2011; Lal, 2004; Zhao et al., 2017). In general, a positive relationship was observed between $\ln R$ of area-scaled CH_4 emission and $\ln R$ of rice yield (Table 2). Thus, the trade-offs between rice cereal production and CH_4 emission

Table 2
Linear relationship between effect sizes ($\ln Rs$) of CH_4 emission with of rice yield or N_2O emission under different management.

Management	CH_4 emission vs rice yield				CH_4 vs N_2O for area-scale				CH_4 vs N_2O for yield-scale			
	n	Coefficient	R^2	*P*	*n*	Coefficient	R^2	*P*	*n*	Coefficient	R^2	*P*
New seedling practices[a]	39	2.3216	0.2668	0.0008	–	–	–	–	24	−0.3292	0.3199	0.004
Herbicide application	–[f]	–	–	–	–	–	–	–	–	–	–	–
Crop rotation[b]	16	10.6741	0.4929	0.0024	–	–	–	–	–	–	–	–
Symbiosis ecosystem[c]	–	–	–	–	–	–	–	–	–	–	–	–
Residue retention	–	–	–	–	105	−0.2712	0.1774	<0.0001	62	−0.2078	0.1036	0.0107
No-till	–	–	–	–	–	–	–	–	–	–	–	–
New rice variety	–	–	–	–	28	−0.7716	0.4771	<0.0001	–	–	–	–
Biochar	40	2.2774	0.1841	0.0057	–	–	–	–	–	–	–	–
Non-flooding irrigation[d]	–	–	–	–	97	−0.409	0.1644	<0.0001	80	−0.4672	0.2861	<0.0001
Organic manure	–	–	–	–	–	–	–	–	–	–	–	–
Amendment input[e]	–	–	–	–	–	–	–	–	–	–	–	–
Nitrogen fertilizer input	158	0.3486	0.0528	0.0037	216	0.3645	0.0269	0.0159	112	1.0644	0.1037	0.0005
Total	720	0.8446	0.0494	<0.0001	741	−0.1467	0.0152	0.0008	479	−0.2155	0.0367	<0.0001

[a] Increase in plant density, postponed seeding date, labor saving seeding methods (by machine and etc.).
[b] Cover crop in fallow season, rotation with upland crops (rice-wheat, rice-maize, rice-rape rotation, and etc.).
[c] Rice-duck, -fish, -floating vegetation system.
[d] Reduced irrigation amount or time, enhanced mid-season drainage.
[e] Nitrification and urease inhibitors, phosphogypsum, methane inhibitor, steel slag etc.
[f] No significant results.

need careful considerations before adopting new field management practices. In addition, according to the average changes, management practices of herbicide application, crop rotation, symbiosis ecosystem, improvement in rice variety, biochar, and amendment input were observed to significantly decrease (or decrease trends) CH_4 emission, as well as significantly increase rice yield (Fig. 1a and b). This trend could be found in previous meta-analysis especially for using new rice varieties (Jiang et al., 2017). That offered possibilities to mitigate CH_4 emission while with enhancing rice yield by combining different field management practices into a system approach. The balance of yield-emission trade-offs in rice production can be built upon the site-specific strategy that adjusting field practices to slow down emissions at yield-scaled will lead to a relatively lower emission and a higher yield.

Generally, CH_4 is a product of organic matter decomposition which driven by soil microbial activities. The anaerobic condition during rice production enhanced the generation of CH_4 (Smith et al., 2008), but drained or well-aerated upland soils could uptake CH_4 (Conrad, 1996). Thus, the different effects of management practices on CH_4 emissions may be due to the attendant effects on soil properties, e.g. aeration, soil structure, soil bulk density (BD), soil porosity, growth of rice root, etc. (Canadell and Schulze, 2014; Smith and Conen, 2004). Indeed, the results indicated reduction in CH_4 emission under non-flooding irrigation was the largest among the 12 paired management practices (Fig. 1a). Reducing the irrigation intensity and the water seal on the surface of field soil, could enhance the soil aeration, increase the redox potential, inhibit the activity of methanogen, and thus, activate the process of CH_4 oxidation (Ball, 2013; Canadell and Schulze, 2014; Smith et al., 2008). However, under the non-flooding irrigation, the growth of rice could be affected negatively may due to the depletion of soil nutrient, non-favorable soil circumstances, and higher aeration, which lead to a decrease in rice yield, when comparing with flooding irrigation (Fig. 1b). Adopting inhibitors or other amendment inputs could also reduce CH_4 emission which were mainly due to the negative effects on methanogen. The presented results showed an average decrease of 16.6% in CH_4 emission under amendment inputs (Fig. 1a). Adopting new rice varieties, CH_4 emission could be reduced along with a higher rice yield (Fig. 1a and b). Similar results were reported by Jiang et al. (2017) that high-yield rice varieties strongly decreased CH_4 emission. This may be attributed to the increased root porosity which could promote the transposition of oxygen into soil profile and the enhanced methane oxidation (Jiang et al., 2017; Ma et al., 2010).

However, the presented results indicated a significant increase in CH_4 emission under residue retention, organic manure application, and N fertilizer input (Fig. 1). Along with more resources from organic or inorganic nutrient input, rice yield could be significantly increased (Fig. 1b). Similar trend was reported by some previous studies (Feng et al., 2013; Liu et al., 2014) that CH_4 emission and rice yield were both increased under residue retention. Their findings may be attributed to increases in C input as the substrates of methanogen and other decomposition progress which led to more CH_4 production and soil nutrients. Effects of N fertilizer on CH_4 producing processes are very complex. Changes in CH_4 emission were the integrative results of increasing in C substrates due to more root exudates, inhibition on methanogen activities, and more NH_4^+ that weakened the CH_4 oxidation process (Schimel, 2000). Furthermore, no significant effects on CH_4 emission were observed with the adoptions of new seedling practices, herbicide application, crop rotation, symbiosis ecosystem, NT, and biochar application (Fig. 1). A previous meta-analysis of China's rice field showed that no significant changes in CH_4 emission were observed under NT (with residue retention) and crop rotation (Zhao et al., 2016). That is mainly due to a comprehensive and complicated changes in soil properties under the practices.

Additionally, our dataset showed a large variation in ln*R*s of CH_4 emission under different practices (Supplementary Dataset). The variation may be induced by the interaction between management practices with site-specific soil/climate conditions of each study. Soil and climate conditions in different regions can also moderate the effects on CH_4 emission and crop yield responding to field management changes (Wassmann et al., 2000; Zhao et al., 2016). Linear regression indicated both positive and negative influences of site-specific environmental conditions (MAP, MAT, BD, SOC, or soil pH) on treatment effects on CH_4 emission for various management practices (Supplementary Table 5). The interactions between soil/climate conditions and practices effects on CH_4 emission was also reported in other meta-analysis. Zhao et al. (2016) reported ln*R*s of CH_4 emission was negatively related to MAT, MAP and positively related to soil pH. Skinner et al. (2014) reported the CH_4 emission was related to MAT, MAP, soil pH, clay, SOC, and N input under organic farming through a meta-regression analysis. Thus, site-specific strategies to maximize the mitigation in CH_4 emission need consider not only the optimization of management practices but also the interactions between soil/climate conditions and practices.

In addition, the meta-analysis results presented herein showed some opposite effects on CH_4 and N_2O emissions under new seedling practices, non-flooding irrigation, and N fertilizer input especially at yield-scaled (Figs. 1c and 2b). Indeed, the results indicated it was difficult to reduce soil-derived GHGs emissions (CH_4 and N_2O) simultaneously by simply changing field management practices. Similar results were also reported in other regional or global meta-analysis and research (Feng et al., 2013; Linquist et al., 2012; Liu et al., 2014; Zhao et al., 2016). The linear relationship analysis showed a generally negative relationship between CH_4 and N_2O emissions at both scales of per area and per yield (Table 2). Thus, to assess the comprehensive effects of field management practices on the effects to mitigating climate change, GWP was the accurate and functional index which could integrate the changes in both CH_4 and N_2O emissions. The results presented herein indicated significant decreases in GWP with non-flooding irrigation, amendment input, and biochar application, but significant increases with residue retention, organic manure application, and N fertilizer input (Fig. 2c). This was mainly because of the differences in resources (crop for residue, plant or/and animal wastes composted for manure) that affected soil and soil microbial progress. However, the adjusting in N fertilizer input (optimize the input amount or time, etc.) may facilitate a larger reduction in GWP by cutting both CH_4 and N_2O emissions (Feng et al., 2013; Linquist et al., 2012). Besides, in rice production, it was ascertained that changes in CH_4 emission could explain a large proportion of changes in total GWP at both area- and yield-scales (Fig. 3) under the 12 management comparisons. Thus, offsetting CH_4 emission should be considered as the main drive for climate change mitigation strategy in rice production, however, altering field management practices also offered potentials for reducing N_2O emission that finally led to a lower GWP system.

The increased atmospheric CO_2 and warming climate will enhance GHGs emissions intensity and decrease rice yield (van Groenigen et al., 2011; van Groenigen et al., 2013; Zhao et al., 2017). The meta-analysis presented herein indicated the possibility of improving field management practices to mitigate GHGs and increase rice yield by enhancing the trade-offs between climate change mitigation and sustaining the global food security. However, some management practices (i.e. increase the inputs of crop residues, manure, and N fertilizer) dramatically increased GHGs emissions even at yield-scaled level in despite of the significant increases in crop yield. Such disadvantages could be offset by altering the management and input of the materials. For example, returning crop residues as mulching on soil surface showed a decreasing trend in area-scaled GWP (Supplemental Table 3); and utilization of controlled release fertilizer or fertilizing at growth stage could significantly decrease the yield-scaled GWP by 27.5% (Supplemental Table 4). Indeed, an optimal input amount and methods of crop residues, N fertilizer, manure and even change of the depth of N fertilizer placement can also benefit rice yield and GHGs mitigation (Feng et al., 2013; Linquist et al., 2012; van Kessel et al., 2013; Zhou et al., 2017). Furthermore, the presented meta-analysis also suggested significant decreases in yield-scaled GWP could be achieved by adopting herbicide,

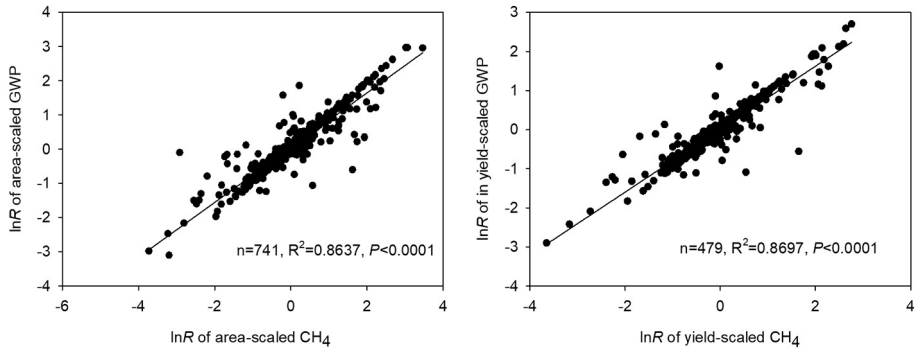

Fig. 3. Relationship between relative changes in CH_4 and GWP (Global warming potential) emission. (a) at area-scaled. (b) at yield-scaled. The scatters are relative change of CH_4 and GWP emissions in response to field management practices changes in our meta-analysis.

biochar, amendments application, or non-flooding irrigation (Fig. 2d). Thus, a systematic field operation may integrate the benefits of reducing GHGs emissions and increasing rice yield.

5. Conclusions

Overall, the findings suggested among 12 evaluated field management practices, non-flooding irrigation obtained the highest efficiency on mitigating GWP, followed by amendment input and improvement in rice variety. Although the reductions in CH_4 emission contributed more to changes in GWP, N_2O emission also could not be ignored. The trade-offs between emission and rice production could be balanced and promoted by optimizing field management practices to adapt and mitigate climate change, and the efficiency might be increased when establishing a systematic field operation to combine the benefits of different individual management practices. In addition, understanding the interactions between different field management practices or between management practices and soil or climate conditions may be essential to realize the potential of altering field management practices to mitigate climate change with sustaining food supply in the furfure.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2018.08.392.

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